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Experimental investigation on pressure drop of supercritical water in an annular channel

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ABSTRACT

This paper presents an experimental investigation of the pressure drop and friction factor of supercritical water in an annular channel. The gap and the full length of the annulus are 4 mm and 1400 mm, respectively. The experimental pressure ranges from 23 to 28 MPa, mass flux ranges from 700 to 1500 kg/(m^{2}s), and heat flux on the inner wall ranges from 200 to 1000 kW/m^2. Results showed that the frictional pressure-drop increases significantly with increasing mass flux, particularly when the bulk enthalpy surpasses the pseudo-critical enthalpy. A local hump in the friction factor was observed corresponding to the pseudo-critical enthalpy, which becomes stronger with the decrease of mass flux or pressure. The assessment of correlations demonstrated that constant-property-based correlations fail to predict the friction factor of supercritical water. Hence, an improved correlation was proposed which captures 82.6% of the experimental data within ± 25% error band.

1. Introduction

Supercritical water is widely used in industrial and engineering fields, such as supercritical boilers, extraction in food processing, and supercritical oxidation in environment protection [1]. In the past two decades, studies have been focused on introducing supercritical water as a reactor coolant. Several conceptual designs of the supercritical water-cooled reactor (SCWR) have been proposed for analysis worldwide by GIF-IV [2]. According to Oka and Koshizuka [3], an SCWR power plant has advantages such as high heat efficiency, low capital investment, simplified loop design, and nuclear nonproliferation. Because of the post-critical operating pressure and temperature, the heat efficiency of an SCWR is expected to reach 45%, which is higher than that of the current pressurized water reactor (33%). Therefore, an SCWR is recognized as one of the most promising water-cooled nuclear systems for the future.

Severe challenges are encountered in the thermal-hydraulic design of an SCWR. Beyond the critical point of water (22.115 MPa, 374.15 °C), the coolant does not undergo phase transition, and consequently, boiling crisis could be eliminated fundamentally. However, the thermophysical properties of supercritical water vary drastically in the pseudo-critical (PC) temperature region. The drastic variations in the fluid density, viscosity, and specific heat lead to strong non-uniform flow features in the flow channel. The issue is more complicated in an SCWR wherein tight fuel bundles are introduced in the conceptual design [4]. The tight rod bundles aggravate the flow imbalances, increase the pressure drop, and affect the flow stability, which need to be further studied.

Many experimental investigations have been performed on the pressure drop of supercritical fluids. Mikheev [5], Chakrygin [6], Tarasova and Leont'ev [7], and Popov [8] reported the basic phenomena of pressure loss inside round tubes and developed correlations to predict the friction factor. These studies showed that the friction factor is mainly a function of the Reynolds numbers. Petukhov et al. [9] conducted an experiment on flow resistance with supercritical carbon dioxide in a heated horizontal tube. The experimental data showed that the pressure drop varies significantly compared to that calculated using a one-dimensional flow model for the deteriorated heat-transfer case. Kurganov et al. [10] experimentally investigated the heat transfer and flow resistance with supercritical CO_2 in vertical upward/downward tubes. They measured the velocity distribution with pitot microtubes, which was used to determine the drag and friction factors and shear-stress distribution. Chen et al. [11] studied the flow pressure-loss of supercritical water in internally ribbed tubes. They reported that the frictional pressure drop increases with the increase of mass flow rate, but it is insensitive to the change of pressure. The general variations in the friction factor with respect to pressure, mass flux, bulk enthalpy and Reynolds number were discussed in detail. Taklifi et al. [12,13] obtained similar findings in the pressure drop experiments on supercritical water in an inclined rifled tube. They gave a detailed analysis of the

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Nomenclature

d	Outer diameter of the heated tube [mm]
D	Inner diameter of the adiabatic tube [mm]
D_e	Hydraulic equivalent diameter [mm]
f	Friction factor [–]
G	Mass flux [kg/(m^{2}s)]
H	Enthalpy [kJ/kg]
L	Pressure-tapping length [m]
P	Pressure [MPa]
Pr	Prandtl number [–]
q	Heat flux [kW/m^2]
Re	Reynolds number [–]
T	Temperature [°C]
W	Mass flow rate [kg/s]

Greek letters

λ	Thermal conductivity [W/(m K)]
μ	Dynamic viscosity [Pa s]
ρ	Density [kg/m^3]

Subscripts

b	Bulk
in	Inlet
PC	Pseudo-critical
w	Wall
out	Outlet

inclination effects on the pressure drop and friction factor. Kirillov et al. [14] studied the friction factor for an isothermal stabilized flow under a near-critical condition. A new correlation incorporating the density modification was proposed to predict the friction factor at the near-critical pressure region. Wang et al. [15] experimentally investigated the heat transfer and flow resistance of the central subchannel in a 2 × 2 rod bundle. The total pressure drop increases with mass flux, particularly when the bulk enthalpy surpasses the PC enthalpy. Zhu et al. [16], Garimella et al. [17], Zhang et al. [18], and Jiang et al. [19] investigated the pressure drop of various supercritical fluids, the results of which are helpful in clarifying the basic characteristics of the friction factor and developing relevant correlations for prediction.

Pioro and Duffey [20] reviewed the experimental studies on the flow pressure drop of supercritical fluids. The review shows that most of the previous experiments were conducted with a simple geometry and very few with complex flow geometry such as annulus or fuel bundle. Regarding the R & D of an SCWR, the flow-resistance characteristics should be clarified to optimize relevant subchannel codes. This will definitely help in obtaining a more reliable and accurate design of the fuel assembly. The present study experimentally investigates the pressure drop of supercritical water in an annular flow channel. The test data have been applied to assess various friction-factor correlations.

2. Experimental facility and method

2.1. Experimental loop

Fig. 1 shows the schematic of the pressure-drop experimental loop. De-ionized water was used as the working fluid, which was pumped into the pipelines using a three-plunger pump. A portion of the fluid was sent back to the water tank for recycling, and the rest flowed into a mass flow meter (precision of 1.02%), a heat exchanger, and a set of preheaters prior to entering the test section. The desired temperature of the test section was obtained by controlling the preheaters. The preheaters and the test section were heated directly by AC power supplies with maximum capabilities of 1.4 MW and 0.5 MW, respectively. The hot fluid at the outlet of the test section was sent to the water tank after it was cooled using the heat exchanger and condenser. During the experiment, the conductivity of the working medium was monitored to ensure a good electrically-insulation.

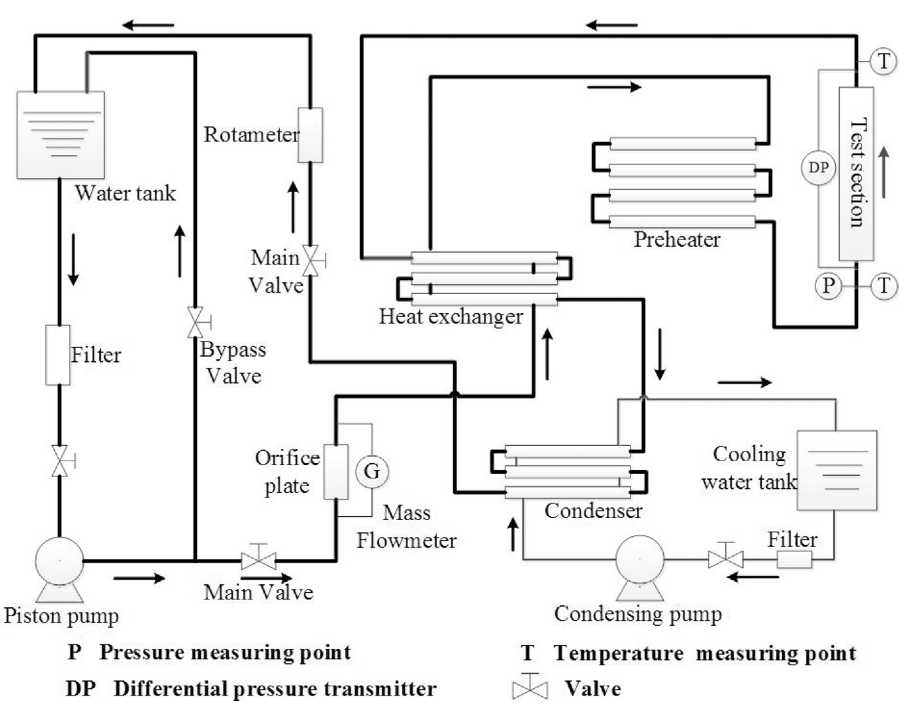

Fig. 1. Schematic of the test loop.